LA-UR -86-2714

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SEP 0 8 1986

CONF-8606204--1

LA-UR--86-2714

DE86 015337

TITLE A REVIEW OF THE CLASSICAL NOVA OUTBURST

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SUBMITTED TO International Astronomical Union Colloquium No. 93

A REVIEW OF THE CLASSICAL NOVA OUTBURST*

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*Supported in part by NSF grants AST83-14788 and AST85-16173 to Arizona State University, by NASA grant NAG5-481 to Arizona State University, and by the DOE.

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Abstract

We review the recent observational and theoretical studies of the nova outburst. The observational studies have not only identified a new class of novae but theoretical simulations of this class have been found to be in excellent agreement with the observations. This new class consists of outbursts occurring on ONeMg white dwarfs in close binary systems in contrast to the other outbursts which are occurring on CO white dwarfs. We also review the effects of the β^+-unstable nuclei and show how their presence has a major effect on the evolution.

I. Introduction

In this review we assume the commonly accepted model for a nova: a close binary system with one member a white dwarf and the other member a larger, cooler star that fills its Roche lobe. Because it fills its lobe, any tendency for it to grow in size because of evolutionary processes or for the lobe to shrink because of angular momentum losses will cause a flow of gas through the inner Lagrangian point into the lobe of the white dwarf. The size of the white dwarf is small compared to the size of its lobe and the high angular momentum of the transferred material causes it to spiral into an accretion disk surrounding the white dwarf. Some viscous process, as yet unknown, acts to transfer mass inward and angular momentum outward through the disk so that a fraction of the material lost by the secondary ultimately ends up on the white dwarf. Over a long period of time, the accreted layer grows in thickness until the bottom reaches a temperature that is high enough to initiate thermonuclear fusion of hydrogen. Given the proper conditions, a thermonuclear runaway (hereafter: TNR) will occur, and the temperature in the accreted envelope will grow to values exceeding 10^8K. The further evolution of the TNR now depends upon the mass and luminosity of the white dwarf, the rate of mass accretion, and the chemical composition of the reacting layer.

Theoretical calculations have demonstrated that this evolution releases enough energy to eject material with expansion velocities that agree with observed values and that the predicted light curves produced by the expanding material can agree quite closely with the observations.

There are many reviews of the observed behavior of a nova in outburst. The classical references are those of PAYNE-GAPOSCHKIN [1] and MCLAUGHLIN [2]. A more recent review is GALLAGHER and STARRFIELD [3]. A very recent review of the nova phenomena in general is treated in BODE and EVANS [72].

2. Novae Abundances

The entire character of the outburst: light curve, ejection velocities, and speed class depends upon the amount of CNO nuclei initially present in the envelope. The fact that a fast nova out-

3. The Effects of the Positron Decay Nuclei

The TNR theory of the nova outburst is an application of nuclear physics to astrophysics [6, 25, 35, 40-45, 68, 76]. One of the most important results of these studies has been the identification of the role played by the β^+-unstable nuclei in the outburst. These four nuclei (^{13}N, ^{14}O, ^{15}O, ^{17}F) influence the outburst in the following fashion: during the early part of the evolution, the lifetimes of the CNO nuclei against proton captures are very much longer than the decay times for the β^+-unstable nuclei ($\tau(^{13}N) = 863s$, $\tau(^{14}O) = 102s$, $\tau(^{15}O) = 176s$, $\tau(^{17}F) = 92$ sec) so that these nuclei can decay and their daughters capture another proton in order to keep the reactions cycling. As the temperature increases in the shell source, the lifetime against proton capture continually decreases until, at temperatures of $\sim 10^8$ K, it competes favorably with the β^+-decay lifetimes. At this time the abundances of these nuclei increases to where they severely impact the nuclear energy generation in the envelope, since every proton capture must now be followed by a waiting period before the β^+-decay occurs and another proton capture can occur. In addition, during the evolution to peak temperature, a convective region forms just above the shell source and gradually mixes the entire accreted envelope. This will carry the β^+-unstable nuclei to the surface and bring fresh unburned CNO nuclei into the hot shell source. As a result, <u>at the peak of outburst the most abundant of the CNO nuclei in the envelope will be the β^+-unstable</u> nuclei.

The large abundances of the β^+-unstable nuclei will have a number of effects on the succeeding evolution. Since the energy production in the CNO cycle comes from a proton capture followed by a β^+-decay, at maximum temperature the rate at which energy is produced will depend only on the number of CNO nuclei initially present in the envelope. This is because the CNO reactions do not create new nuclei, but only redistribute them among the various CNO isotopes [40]. The rate of energy production at maximum can then be expressed as [15]:

$$\varepsilon_{cno} = 6 \times 10^{15} \; Z_{CNO} \; \text{erg/gm/s} \quad .$$

The convective turnover time scale is so short that a significant fraction of the β^+-decay nuclei can reach the surface and, therefore, the rate of energy generation at the surface can reach 10^{12} to 10^{13} erg/gm/sec [25].

These nuclei also have the effect of "storing" energy for release on very long time scales compared to the dynamical time scale of the envelope. Once peak temperature is reached and the envelope begins to expand, one would expect the rate of energy generation to drop precipitously. However, in realistic calculations, which include a detailed calculation of the abundance changes with time of the nuclei, the rate of energy generation declines only as the abundances of the β^+-unstable nuclei decline since their decay is neither temperature nor density dependent. In fact, the numerical calculations done with burst demands enhanced CNO abundances was one of the first and clearest predictions of the TNR theory of the nova outburst. We mention this point in order to emphasize the predictive nature of the TNR theory.

As late as 1977 (after the original papers on the TNR theory had appeared in print) a review was published which claimed that there was still no secure evidence for nonsolar abundances in novae [19]. Shortly thereafter, Williams and Gallagher and their collaborators began a series of investigations of nova shells from which the general conclusion was that not only were nova shells enhanced in the CNO nuclei but that there was a correlation between degree of enhancement and nova speed class [5, 19-22]. Studies of HR Del [23] and V1500 Cygni [24] have strengthened this correlation. A summary of the observed abundances for novae can be found in WEISCHER *et al.* [17] and in TRURAN AND LIVIO [75]. One counterexample to the CNO enhancement versus speed class relationship is DQ Her [20] which shows a very large enhancement of carbon although it was a slow nova. The explanation is that the white dwarf is of considerably lower mass than found in typical nova systems [5, 25].

Studies of recent novae have led to some very interesting, if not perplexing, results. A most unusual recent outburst was that of the recurrent nova U Sco [27, 28], which at maximum showed strong H_β and HeII, but at minimum showed only lines of helium. The optical data imply that He/H in the ejecta was ~ 2 (by number). While the UV data imply nearly normal CNO abundances, they also imply that only ~ 10^{-7} $M_\odot$ to 10^{-8} $M_\odot$ was ejected during the outburst. U Sco was an extremely fast nova, declining by more than eight magnitudes in one month, and its ejection velocities may have exceeded 10^4 km/sec. Most surprising, spectra obtained much later, at minimum, suggest that either only helium is being transferred by the secondary or that this nova has found some way to hide the presence of hydrogen in an apparently normal accretion disc. Note also that this object provides evidence for evolved secondaries in cataclysmic variables.

Of great importance to our understanding of the nova outburst, have been the recent studies of nova using the *International Ultraviolet Explorer* Satellite. These studies include that of Nova Cygni 1978 which not only showed enhanced CNO [34] but the derived abundances were in agreement with the theoretical calculations of STARRFIELD, SPARKS, and TRURAN [35]. There have also been studies of V603 Aql [32], U Sco [28]; Nova V693 CrA 1981 [36, 70] and Nova V1370 Aql 1982 [37, 71]. All of these novae showed very unusual abundances in the ejecta. The interpretation of V693 CrA and V1370 Aql is that they ejected core material from an oxygen, neon, magnesium white dwarf that had been processed through a hot hydrogen burning region by the nova outburst [76]. Reviews of the ultraviolet observations can be found in [76, 77].

The observation that the $^{12}C/^{13}C$ isotopic ratio in DQ Her was also far from solar [39] supports the TNR theory as the cause of the outburst and indicates that the nuclear reactions have proceeded in a very non-equilibrium fashion as has been predicted for novae [38, 35].

enhanced CNO nuclei [25] show that more than 10^{47} erg is released into the envelope after its expansion has begun. The envelope reaches radii of more than 10^{10} cm before all of the ^{13}N has decayed. Therefore, the decay of the β^+-unstable nuclei provides a delayed source of energy which is ultimately responsible for ejecting the shell. Finally, since these nuclei decay when the temperatures in the envelope have declined to values that are too low for any further proton captures to occur, the final isotopic ratios in the ejected material will not agree with those ratios predicted from studies of equilibrium CNO burning.

The discussion up to this point has not required the assumption of enhanced CNO nuclei but is based on the hypothesis that in order for an outburst to occur the shell source will be degenerate enough so that the peak temperature exceeds 10^8 K. If this occurs, the effects of the β^+-unstable nuclei become inevitable. However, the observational fact that the CNO nuclei are enhanced in the ejecta also requires them to be enhanced in the nuclear burning region. All of our arguments about the effects of the β^+-unstable nuclei are only strengthened if the CNO nuclei are enhanced. Peak energy generation is increased, more energy is stored for release at late times in the outburst, and the resulting isotopic and elemental ratios in the ejecta will be very unusual. We have found that enhanced CNO nuclei are required to power a fast nova outburst and, in fact, no calculation at a mass of 1.3 $M_\odot$ or less, using only a solar mixture, has been successful in reproducing a realistic fast nova [5].

4. A Theoretical Nova Outburst

a) The rise to bolometric maximum

The initial phase of the rise to maximum of the outburst occurs very rapidly and is determined by the convective turnover time scale in the envelope. The calculations show that once the shell source temperature reaches $\sim 2 \times 10^7$ K, a convective region forms just above the shell source and gradually grows toward the surface as the shell source temperature continues to increase. Up to this point, no sign of the impending explosion has reached the surface. However, when the temperature in the shell source passes $\sim 10^8$ K, the convective region finally reaches to the surface and the energy and β^+-unstable nuclei, produced in the deep interior, can now increase the surface luminosity. Since the surface layers are very thin (10^{-8} $M_\odot$ or less), the luminosity can reach or exceed 10^5 $L_\odot$. At this time the envelope is expanding at velocities of 1 to 10 km/sec and cannot have expanded very far, so that its radius is still small and the effective temperature is $\sim 5 \times 10^5$ K. Therefore, novae at bolometric maximum will be very luminous EUV or soft x-ray sources.

b) Rise to visual maximum

Once the outburst has reached its peak, both in nuclear energy production and in shell source temperature, the envelope begins to expand. It is also likely for fast novae that the surface luminosity exceeds the Eddington luminosity hastening the change from hydrostatic equilibrium to hydrodynamic expansion. All simulations of the nova phenomena which assume only hydrostatic motion break down at this point.

Peak visual luminosity occurs when the luminous, expanding shell reaches its maximum effective radius; $\sim 10^{12}$ cm to 10^{13} cm. This radius is determined by the expanding gas cooling until a temperature $\sim 7\text{-}9 \times 10^3$ K is reached. At this point hydrogen recombines and the opacity drops rapidly so that the effective photosphere then begins to move inward with respect to mass fraction [3, 49, 50]. The time from peak temperature in the shell source to peak visual luminosity depends on the rate of expansion of the envelope. The observational data imply that there is in general an inverse correlation between speed class and time to maximum in that the faster novae expand more rapidly and reach visual maximum faster than do the slower novae. We attribute such a correlation to the fact that the rate of expansion must depend on the ratio of the nuclear energy release per gram during the final stages of the TNR to the binding energy per gram of the envelope. The more the CNO nuclei are enhanced, the more rapid the energy release during the early stages of the outburst.

c) The constant bolometric luminosity phase

This phase was first discovered by GALLAGHER and CODE [52] and extended to other novae by GALLAGHER AND STARRFIELD [53]. It is one of the most important predictions of the TNR theory for the classical nova outburst [3-6, 25]. What was predicted and what the UV [34, 36, 54] and IR observations [55, 57] show is that the bolometric light curve of a typical nova is uncorrelated with the visual light curve. In the observational studies one finds that a typical nova energy distribution hardens as the visual magnitude declines resulting in an increasing fraction of the energy being emitted outside the optical region of the spectrum as the outburst progresses. The total luminosity remains constant or declines only slightly, while the visual light curve declines by large factors. Thus, the visual light curve is a poor indicator of the total energy emitted during the nova outburst.

The physical cause of this phenomena, as predicted by the numerical calculations, is as follows: only 10% to 50% of the accreted material is ejected in the initial outburst. Once the shell has been ejected, the material remaining on the white dwarf returns to hydrostatic equilibrium. The remnant is now radiating energy at close to the Eddington limit and the calculations show that the luminosity depends on the core mass and that the radius depends on the envelope mass. The larger the amount of mass remaining on the white dwarf, the larger the radius of the remnant envelope. The decline in visual magnitude can then be understood as a shift of the peak energy into the UV and then the EUV. If we identify the luminosity from this phase of the outburst with the plateau luminosity as discussed by IBEN [12], then it becomes possible to estimate the white dwarf mass based on a determination of the total energy output at this time [13].

hydrogen rich envelope of a white dwarf. The most important evidence in favor of this theory has been the predictions and confirmation both of enhanced CNO nuclei in the ejecta and of a constant luminosity phase in the outburst. Observational support has also come from the discovery of a correlation between speed class and CNO enhancement. In addition, calculations of the light curves for slow novae and most fast novae show excellent agreement with observed light curves with some exceptions. The theoretical simulations show that given a white dwarf with a specific envelope mass and elemental enhancement it is possible to eject material and that this material has velocities and kinetic energies in the range of observed values.

One of the most interesting features of the TNR theory for the nova outburst has been the identification of the importance to the outburst of the positron decay nuclei (^{13}N, ^{14}O, ^{15}O, ^{17}F) whose half-lives, all on the order of minutes, determine the character of the outburst. Given the properties of the nuclear reactions and the predicted abundances as a function of nova speed class, we turned to the observational evidence for confirmation or denial of the predictions. In fact, the recent studies of nova shells and the UV observations of novae in outburst demonstrate that such a correlation exists with two notable exceptions: DQ Her and Nova VUL 1984 #2. Analysis of the spectrum of DQ Her near maximum indicated nonsolar $^{12}C/^{13}C$ and $^{14}N/^{15}N$ isotopic ratios; the strongest evidence for the operation of a TNR in the nova outburst. The existence of this object underscores the wide variety of initial conditions that are possible in a nova. The theoretical studies have shown that even a massive enhancement of carbon in the accreted envelope of a low mass white dwarf ($M \leq 0.9\ M_{\odot}$) can only produce a slow nova. Further observational studies of novae show that carbon, nitrogen, and oxygen are definitely enhanced in novae, and that neon and helium are enhanced in some novae. Finally, there has been a prediction that ^{7}Li should be enhanced in novae ejecta [67] but confirmation of that prediction must wait until new detection schemes are devised.

The theoretical calculations that were presented in this review illustrate all of the physical processes that have been identified as relevant to the outburst. We find that the cause of the constant UV luminosity from novae is that a fraction of the accreted envelopes is not ejected during the burst stage of the outburst. This material is hot ($T_e = 10^5$ K), luminous ($L \sim L_{ed}$), and evolving on a nuclear time scale. In order for the outburst to end, this material must be ejected both by a wind and also by dynamical friction. Once we have modeled this phase of the outburst, then we shall have a means of predicting the secular evolution of the white dwarf in nova binaries and, thereby, determining whether it is losing or gaining mass as a result of the outburst.

This review has greatly benefitted from discussions with Drs. J. Truran, J. Gallagher, S. Kutter, and R. Williams. We would also like to thank Drs. M. Bode, F. Cordova, A. N. Cox, R. Gehrz, J. MacDonald, E. Sion, E. Ney and H. Van Horn for valuable discussions. Support from the National Science Foundation through grants AST83-14788 and AST85-16173 to ASU from the Association of Western Universities and

However, it is also the case that some fast novae exceed not only this luminosity, but also the Eddington luminosity during the early stages of the outburst. One such case was Nova V1500 Cygni 1975 whose luminosity at maximum exceeded $7 \times 10^5 L_\odot$ [54]. Its photospheric radius, shortly after maximum, was estimated to be $\sim 2 \times 10^{13}$ cm, which is consistent with an expansion velocity of $\sim 1.2 \times 10^3$ km/sec [59]. A value of this magnitude emphasizes the requirements for overabundances of the CNO nuclei [53]. A similar analysis shows that Nova V1668 Cygni 1978 must have also exhibited a super-Eddington phase [13].

d) The turn-off phase

In the last stages of the outburst the white dwarf must rid itself of enough material to halt nuclear burning in the shell so that the remaining material will collapse back onto the white dwarf. It is also during this stage that the accretion disc reestablishes itself and the system begins evolving to another outburst in 10^4 to 10^5 years [63]. Both observations and theory suggest that two mechanisms are operating at this time to drive off the remnant envelope. The first is stellar wind type mass loss [61, 64, 73], which can drive mass loss rates as high as 10^{-6} to 10^{-7} $M_\odot$/yr for our luminous remnants. This rate will be increased if carbon, nitrogen, and oxygen are enhanced in the envelope since the rate depends on the number of strong lines present in the UV.

Another process, considered in detail by MACDONALD [65], see also [4, 25, 73], is that the radius of the expanded white dwarf exceeds the radius of the binary system during the early stages of the outburst. Dynamical friction, caused by the secondary orbiting within the outer radius of the remnant, will then drive mass loss [65]. This process continues until the equilibrium radius of the remnant shrinks within the roche lobe of the white dwarf. At this time tidal forces from the secondary could possibly act to drive some additional mass loss.

The amount of material which remains on the white dwarf after an outburst also impacts the secular evolution of the white dwarf. Since the outbursts of fast novae require that 10% to 30% of the accreted envelope must be CNO nuclei, probably mixed up from the CO or ONeMg core, and that each outburst ejects a significant fraction of the envelope plus core material, then we are forced to the conclusion that the long term evolution of a fast nova is to slowly whittle away the core. For slow novae, which do not show enhanced abundances and probably eject only by a wind plus dynamical friction [42, 65], it is possible that there is no mass lost from the white dwarf and that the secular evolution of the system produces a thick helium layer on the white dwarf. This question is still open.

5. Numerical Calculations of a Nova Outburst

The most detailed calculations of the TNR theory for the nova outburst are found in a series of papers by STARRFIELD, SPARKS, and TRURAN [25, 42, 68, 69]. Here we summarize these papers. The initial model for our first studies had the envelope in place and in both thermal and hydrostatic equilibrium. The difference between this approach and the "accretion" approach, where hydrogen rich material is gradually added to the surface layers, is discussed in detail in STARRFIELD et al. [46] The main effect of this difference is on the time scale to outburst. The envelope masses found in the "in place" studies are quite comparable to those of the "accretion" studies. In fact, we have used various envelope masses in our computations. A more serious problem with some other published "accretion" studies is that they have used equilibrium CNO reaction rates which is an unrealistic assumption for the most important stages of the outburst.

Also, in our studies, we have assumed a variety of white dwarf masses all of which are larger than the commonly accepted value of 0.6 $M_\odot$ for single white dwarfs [66]. This is because the white dwarfs in close binaries appear to have masses > 1.0 $M_\odot$ [13].

We describe only one evolutionary sequence ($M_e = 10^{-4}$ $M_\odot$) in any detail. It took ~ 10^3 years to reach the peak of the TNR. During this time a convective region formed just above the shell source (it first appeared when the shell source temperature reached 2.5 x 10^7 K) and grew slowly toward the surface (1 month). It reached the surface just when the shell source temperature passed 6 x 10^7 K. The energy release from the β^+-unstable nuclei caused the rate of energy production at the surface to reach 10^{13} erg/gm/sec and this heating accelerated the surface layers to expansion velocities of 8 km/sec. This sequence ejected 3.5 x 10^{-5} $M_\odot$ moving with speeds from 35 km/sec to 3200 km/sec; a kinetic energy of 6 x 10^{44} ergs. The ejected mass amounted to 32% of the initial envelope. Peak bolometric magnitude was $-11^m.4$ while peak visual magnitude was $-7^m.5$ [25]. The light curve is published in [25]. These values fall well within those observed for normal fast novae.

We have also considered models with a different degree of CNO enhancement. In fact, in all of our studies we have determined the minimum degree of enhancement necessary to produce an outburst and eject material with a nova type light curve. We find that for a given white dwarf mass and envelope mass, that the strength of the outburst is strongly correlated with the degree of CNO enhancement. As we increase the enhancement, the peak shell source temperature, the amount of ejected material, and the ejection velocities all increase.

In another study we investigated the effects of no CNO enhancement as a proposed model for the slow nova outburst [42]. We followed the evolution of a 1.25 $M_\odot$ white dwarf with an envelope mass of 1.25 x 10^{-4} $M_\odot$ and assumed only a solar mixture (Z = .015). The entire evolution occurred on a much longer time scale than for a fast novae. One of the most exciting features of this study was that we achieved mass ejection from radiation pressure and that the theoretical light curve agreed quite closely with the observed light curve of Nova HR Del 1967. The simulation took about 10^6 sec to evolve to high luminosities and reached the plateau luminosity (L_p) as discussed by IBEN [12]. Similar behavior was found in other studies of slow novae [43, 45, 65]. However, as pointed out by MACDONALD [65], these calculations neglected dynamical friction. Since the extended envelope of the slow nova sequence [42] exceeded L ~ 10^{12} cm, this will certainly be an important effect in any slow nova studies. Nevertheless, this sequence did eject material and the theoretical calculations did resemble a very slow nova outburst.

We have also evolved TNR's on massive white dwarfs (1.38 $M_{\odot}$) in a successful attempt to produce outbursts which resemble those of the recurrent nova U Sco [68]. We used the spherical accretion code of KUTTER and SPARKS [16] to accrete solar composition material at a variety of rates onto white dwarfs with various luminosities. Our results produced sequences that took less than 40 years to reach the peak of the outburst and then ejected material by radiation pressure. The amount of material ejected is in good agreement with the observations. A light curve for one such sequence is published in STARRFIELD, SPARKS, and TRURAN [68].

For our most recent studies, we have developed a new accretion code which is very fast and accurate. We have used it to study accretion and the resulting thermonuclear runaways on 1.25 $M_{\odot}$ white dwarfs with a range of white dwarf luminosities and rates of mass-accretion. We have also utilized four different compositions for the accreting material. One mixture was used to simulate an O-Ne-Mg white dwarf.

All of the solar accretion evolutionary sequences resulted in a thermonuclear runaway and a rapid rise in luminosity. However, the sequences which utilized very luminous white dwarfs: L> 0.1 $L_{\odot}$ did not eject any material and the accreted envelope quickly burned to pure helium. Therefore, accretion onto luminous, i.e., young white dwarfs will produce a growing layer of helium on the surface of the white dwarf. Accretion onto low luminosity white dwarfs for $\dot{M} < 10^{-8}$ $M_{\odot}$/yr produced ejection but a significant fraction of the accreted envelope remained on the white dwarf and again resulted in a growing layer of helium on the surface.

The evolutionary studies done with the envelope consisting of half solar material plus half carbon and oxygen or half solar material plus half carbon produced very similar results. Accretion onto luminous white dwarfs produced an outburst, but no mass was lost and a major fraction of the outburst luminosity was radiated in the EUV. Because carbon is so highly reactive, the runaway occurred before the envelope had accreted sufficient material to become degenerate and only a "weak" outburst occurred. At low white dwarf luminosities and small mass accretion rates, an outburst occurred and a major fraction of the envelope was ejected. The evolutionary sequences done with half solar composition plus half oxygen were equivalent to the other studies of accretion onto high luminosity white dwarfs. However, on low luminosity dwarfs for the same $\dot{M}$, the outbursts were much more violent and a much larger fraction of the accreted envelope was ejected [69].

6. Summary and Discussion

In this review we have presented both the theoretical and observational evidence that leads to the inescapable conclusion that the classical nova outburst is the direct result of a TNR in the accreted hydrogen rich envelope of a white dwarf. The most important evidence in favor of this theory has been the predictions and confirmation both of enhanced CNO nuclei in the ejecta and of a constant luminosity phase in the outburst. Observational support has also come from the discovery of a correlation between speed class and CNO enhancement. In addition, calculations of the light curves for slow novae and most fast novae show excellent agreement with observed light curves with some exceptions. The theoretical simulations show that given a white dwarf with a specific envelope mass and elemental enhancement it is possible to eject material and that this material has velocities and kinetic energies in the range of observed values.

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from the Joint Institute for Laboratory Astrophysics, is gratefully acknowledged. S. Starrfield would like to thank Drs. G. Bell, S. Colgate, M. Henderson and J. Norman for the hospitality of the Los Alamos National Laboratory.

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